

Insights into residential EV charging behavior using energy meter data

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ABSTRACT

Mass adoption of the plug-in electric vehicle (EV) technology is imperative for the rapid electrification of the transportation sector to mitigate catastrophic effects from climate change. Rapid integration of a large number of EVs will inevitably cause uncertainty and variability on the operation of the existing electric power system. There is high uncertainty on not only the speed and scale of EV adoption but also the EV energy and power requirements that depends on EV charging patterns. This study uses energy meter-level data from the San Diego region to analyze the energy load profiles of residential customers under the time-of-use (TOU) rate with and without EV charging requirements. Unlike previous forecasts on the effects of EV charging loads, the energy load profile of TOU customers with EVs reveal a “twin demand peak” where there is a peak demand during the evening hours and another at midnight. Results reveal potential issues for grid operations with greater EV adoption and the importance of careful TOU rate design.

1. Introduction

Major studies have demonstrated the urgent need for a rapid electrification of the transportation sector to mitigate catastrophic effects from climate change (DOE, 2010; MIT, 2010; Slezak, 2013). Large reductions in greenhouse gas (GHG) emissions from the transportation sector requires a mix of technology solutions including a rapid electrification of the passenger vehicle sector to reach emissions reduction targets (NRC, 2013). Governments around the world have taken direct action to promote the adoption of the plug-in electric vehicle¹ (EV) using new legislation, tax incentives, and other policy instruments. California's Governor Brown has initiated the zero-emission vehicle (ZEV) mandate that targets the deployment of 1.5 million ZEVs by 2025 (CARB, 2018). Rapid integration of such a large number of EVs will inevitably cause uncertainty and variability on the operation of the existing electric power system. There is high uncertainty on not only the speed and scale of EV adoption but also the EV energy and power requirements. Furthermore, there is an additional unknown human factor in the anticipated mass adoption of EVs that clouds the forecasted charging load requirements: when will EV drivers actually charge their vehicles? These uncertainties have contributed to a condition where there is no clear roadmap on building the appropriate EV charging infrastructure that must be strategically constructed to foster a rapid, seamless transition to transportation electrification.

1.1. Literature review on EV charging behavior

Numerous studies have attempted to model and estimate EV charging loads under various scenarios. These studies must make certain assumptions on the daily EV charging patterns that are often difficult to validate. Many studies formulate charging scenarios without any actual EV charging data; rather, the scenarios are built based on factors such as travel patterns. A number of studies use survey travel data to create charging scenarios. Sioshani and Denholm (2009) considered the “wherever, whenever” charging case where charging occurs whenever vehicles are parked based on travel survey data of the St. Louis metropolitan area. Wang et al. (2017) forecasted the EV charging demand using synthetic U.S. travel data and electricity pricing. Kang and Recker (2009) used the 2000–2001 California Statewide Household Travel Survey to consider four different scenarios including the case where vehicles charge whenever they are parked as well as controlled off-peak and public charging cases. Axsen et al. (2011) used a sample of travel survey data of new vehicle buyers in California to consider three different charging scenarios and also incorporated the availability of an electrical outlet within 25 feet as a prerequisite to charging. Kim and Rahimi (2014) used travel pattern data at the city level to determine when EVs would be available for charging then assumed different EV charging scenarios. Weiller (2011) used the National Household Travel Survey to create uncontrolled and delayed charging scenarios where restrictions are placed on certain charging times. Kelly et al. (2012) expanded on Weiller's recharging scenarios by incorporating

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¹ In this article, the term “EV” refers strictly to plug-in electric vehicles.

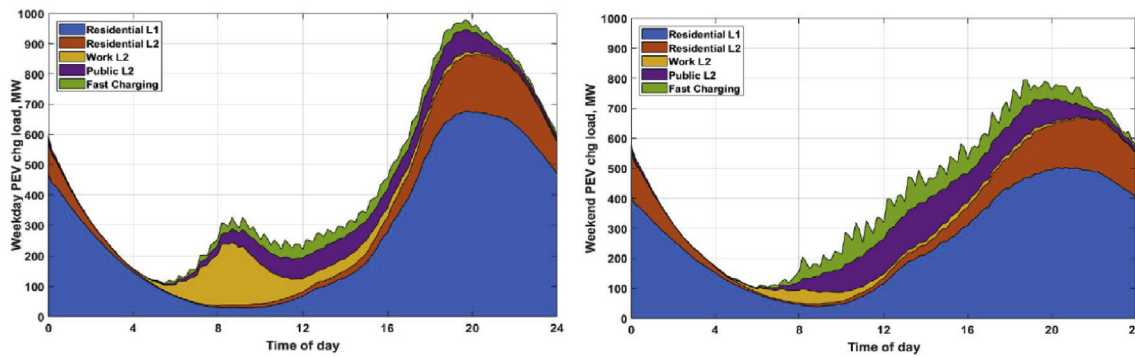


Fig. 1. Forecast of California's EV charging loads for a typical weekday/weekend in year 2025 (CEC, 2018b).

demographic influences on charging behavior. There are also studies that assume an ideal scenario where charging primarily occurs during late night or the “off-peak” hours so that the overall energy load becomes more leveled (EPRI, 2007; Kintner-Meyer et al., 2007; Stephan and Sullivan, 2008).

Recently, the California Energy Commission (CEC) released a major study on anticipating the required EV charging infrastructure to support the increasing number of EVs on the road (see Fig. 1). One of the key results from the study is that the expected peak EV charging load is nearly 1 GW at 7:40 p.m. on a weekday for the entire state. The expected peak on weekends is nearly 800 MW at 6:50 p.m. These results suggest that EV charging would add to the existing regional load and increase peak demand, exacerbating the existing problems associated with excess renewable generation and rapid generation ramping.² The vast majority of the EV charging is expected to take place at people's homes (i.e., residential). Therefore, the effect from residential EV charging (L1 & L2) is expected to be significant in both the total energy load and the shape of the load profile (see Fig. 1). One key takeaway from this study is that the forecast of EV charging loads primarily hinges on the assumption that EV drivers charge their vehicles based on travel patterns. That is, most EVs begin charging when EV drivers arrive at home after work during peak hours (approximately 5–8 p.m.). This study attempts to shed light on this assumption using actual meter-level energy data from EV owners. Strong evidence against such charging behavior assumption would have significant impact on the validity and accuracy of the EV charging load forecasts, which would consequently have an impact on energy policy.

1.2. SDGE energy load profile

This article focuses on the San Diego Gas & Electric (SDGE) service territory that serves an area spanning from San Diego County to parts of Orange County (see Fig. 2). SDGE is one of the three major investor-owned utilities (IOU) in California. It supplies power to roughly 1.4 million businesses and residential customers in a 4,100 square-mile service area (SDGE, 2018a).

SDGE's load profile is primarily composed of 4 sectors: commercial & industry, residential, agriculture, and others (e.g., street lights). A summary of the energy consumption by each sector is shown in Table 1.

Although the overall energy consumption is dominated by the commercial/industry sector, the overall load shape is disproportionately affected by the residential sector. For example, the peak demand occurs when the residential load reaches its peak (roughly between 5 and 8 p.m.) throughout the year (see Fig. 3). Therefore, changes to the residential load profile would have a significant effect on the overall system peak and load profile.



Fig. 2. Map of the SDGE service territory in Southern California (source: SDGE, 2018a).

1.3. SDGE rate groups

There are roughly 30 different billing rate groups within the residential customers in the SDGE service territory. Many billing rates are special rates with very few actual customers. The majority of the residential customers fall under the “DR” rate group.³ There are numerous time-of-use (TOU) rate groups. Within the TOU group, there are also specific rate groups that are designated explicitly for residential customers who charge an EV(s) on the premise.

1.3.1. Standard rate plan (DR)

The DR rate group is the default rate plan for residential customers. It is a tiered-pricing system with increasing rates with increasing usage. Each customer is given a monthly baseline usage allowance based on their location (i.e., climate zones). If a customer exceeds the baseline allowance by a certain threshold, then the rates increase from Tier 1 to Tier 2. There is a range of allowable usage within Tier 2. Once a customer exceeds the Tier 2 range, then the rates increase to the high usage charge (HUC) level. An example of SDGE's DR Tier ranges is shown in Fig. 4.

The baseline allowance and the high usage charge threshold vary depending on the region and time of year. The coastal regions classified as the “coastal” climate zone have the lowest baseline allowance because it enjoys milder temperatures (less cooling and heating needs).

³ DRLI is also included which is comprised of DR customers who qualify for California's CARE program for low-income households. See <http://www.cpuc.ca.gov/General.aspx?id=976> for more information.

² Often referred as the California “duck curve” (CAISO, 2016).

Table 1
Annual energy consumption by sector in SDGE service territory (data source: CEC, 2018a).

| Year | Commercial/Industry | | Residential | | Agriculture | | Others | |
|------|---------------------|----------|-------------|----------|-------------|----------|--------|----------|
| | GWh | (%Total) | GWh | (%Total) | GWh | (%Total) | GWh | (%Total) |
| 2014 | 13,319 | 62.14 | 7,670 | 35.79 | 349 | 1.63 | 94 | 0.44 |
| 2015 | 13,434 | 62.42 | 7,682 | 35.70 | 315 | 1.47 | 90 | 0.42 |
| 2016 | 13,193 | 62.42 | 7,553 | 35.73 | 310 | 1.47 | 81 | 0.38 |

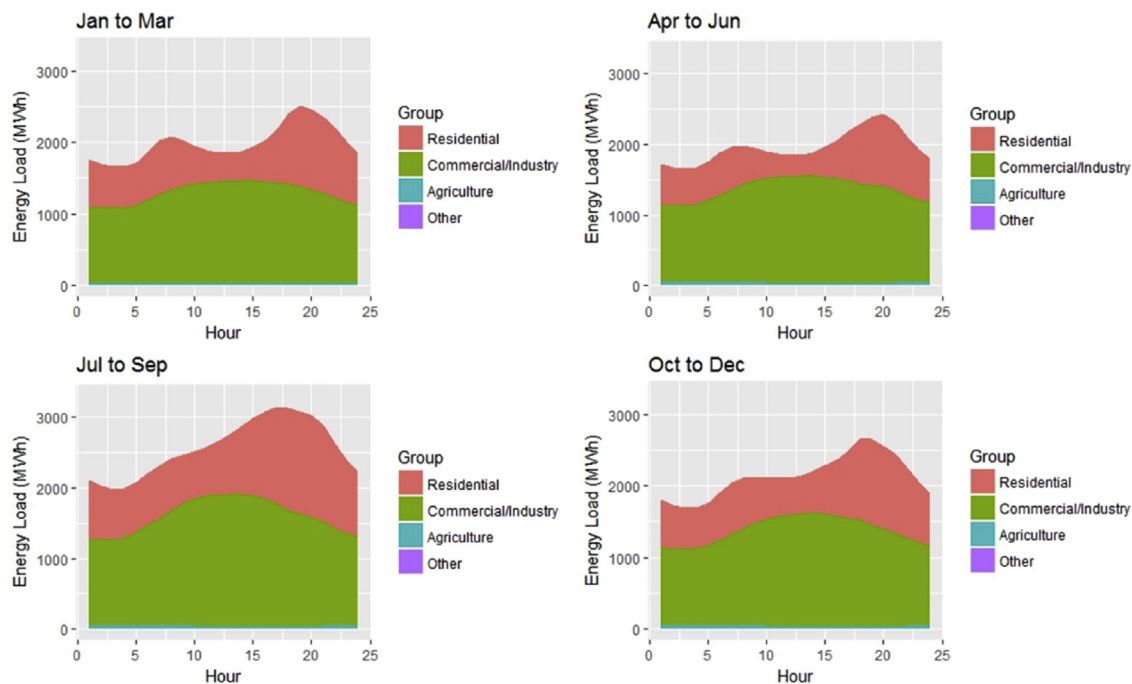


Fig. 3. Average daily energy load in SDGE service territory based on consumer sector.

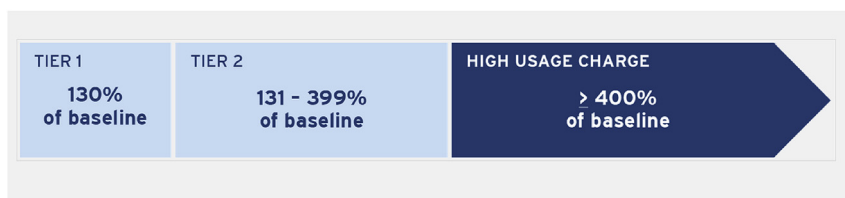


Fig. 4. Example of SDGE's standard residential rate plan structure based on usage (source: SDGE, 2018b).

Table 2
Example of baseline allowance and high usage charge in the SDGE territory in 2018.

| Climate Zone | Summer | | Winter | |
|--------------|--------------------------|-------------------------|--------------------------|-------------------------|
| | Baseline Allowance (kWh) | High Usage Charge (kWh) | Baseline Allowance (kWh) | High Usage Charge (kWh) |
| Coastal | 249 | 996 | 405 | 1620 |
| Inland | 303 | 1212 | 474 | 1896 |
| Mountain | 495 | 1980 | 780 | 3120 |
| Desert | 555 | 2220 | 600 | 2400 |

Inland regions progressively have higher baselines allowances because of the higher temperatures (higher cooling and heating needs). The allowances are higher in the winter months because the overall system load is significantly lower (see Fig. 3). A summary of the baseline allowance and high usage charge thresholds are shown in Table 2.

1.3.2. Time-of-use (TOU) plans

SDGE offers time-of-use (TOU) pricing plans to its residential customers. In a standard TOU plan, each day is broken into on-peak and off-peak time zones with energy costing less during the off-peak hours. Similar to the standard DR plan, the TOU plans are also tiered plans so if a customer exceeds the baseline allowance by a certain threshold, the rates increase.⁴ An example of the tier pricing structures in TOU plans is shown in Fig. 5.

TOU rate structure

Within the TOU pricing plans, there are numerous types and variations that are often a result of experimental rates becoming permanent, updated, or removed in subsequent years. Much of the difference between these plans are minimal within the time frame of this study so the TOU plans are grouped into two main types for brevity: TOU and EVTOU.

- TOU – This is the default TOU rate plan. The plan has a “peak” and

⁴ Under the SDGE TOU rate plans, there are two tiers rather than three.

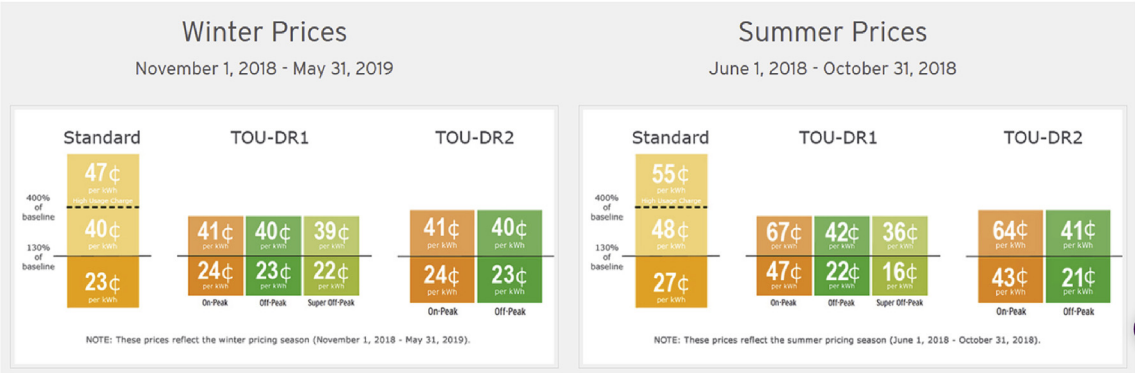


Fig. 5. Example of SDGE's TOU pricing plan for residential customers (source: SDGE, 2018c).

- “off-peak” time intervals with different rates.
- EVTOU – This type of plan is intended for residential customers with electric vehicle (EV) charging loads.

Under each TOU plan, there are specific hours (“blocks”) that correspond to a time-dependent rate. Examples of such time blocks are off-peak, on-peak and semi-peak hours. These time blocks can vary depending on the day of the week (e.g., weekday vs. weekend) and time of the year (summer vs. winter). A visual mapping of the different time blocks for each TOU rate plan is shown in Tables 3 and 4. For all plans, the time blocks corresponds to the study's scope, which is from January 1st, 2016 to December 31, 2017. Based on survey of EV owners, roughly 73% of EV owners were under some type special EV electric rate plan between the years 2013 and 2015 (CSE, 2018). It is highly likely that this percentage is even higher for the study's time span and future years due to greater awareness and availability of EVTOU plans.

One of key features revealed in the mapping of the TOU time blocks is the consistent penalty on energy consumption during late afternoon/evening hours with the “on-peak” rates (see Tables 3 and 4). There is also a consistent incentive for higher energy consumption with the “super off-peak” rates typically from midnight to early morning.

2. Methodology and data

Meter-level electricity consumption data for rate payers in the SDGE service territory was collected for the year 2016 and 2017. The analysis presented in this article has a scope that is limited to residential load data, which includes energy consumption in 1-hour intervals.

Table 3
Typical weekday time blocks under TOU plans.

| Rate Class (Year) | Rate Plan | 12 a.m. | 4 a.m. | 8 a.m. | 12 p.m. | 4 p.m. | 8 p.m. |
|-------------------|-----------|---------|--------|--------|---------|--------|--------|
| TOU (2016) | DR-TOU | | | | | | |
| | TOU-DR | | | | | | |
| EVTOU (2016) | EV-TOU | | | | | | |
| | EV-TOU2 | | | | | | |
| | DR-E1 | | | | | | |
| | DR-E2 | | | | | | |
| | DR-E3 | | | | | | |
| TOU (2017) | DR-TOU | | | | | | |
| | TOU-DR1 | | | | | | |
| | TOU-DR2 | | | | | | |
| EVTOU (2017) | DR-E1 | | | | | | |
| | DR-E3 | | | | | | |

On-Peak

Semi-Peak

Off-Peak

Super Off-Peak

Other - Single Rate

2.1. Regional data coverage

This study includes meter level data of roughly 1.5 million residential customers across the city of San Diego and two out of four “climate zones”. The SDGE service territory is divided into 30 different specialized regions designated as “Towns”. Town 1 is the largest region which captures the city of San Diego. Each Town can span across multiple climate zones. For example, the city of San Diego is Town 1 but spans across climate zones 1, 2 and 4.

The number of data points vary depending on each Town and rate group. This study focuses on three regions – city of San Diego (Town 1), Coastal Zone and Inland Zone. Both the Coastal and Inland Zones exclude customers from Town 1 (i.e., city of San Diego). The Mountain and Desert Climate Zones are excluded from the study because of potential privacy issues due to the small number of customers for the TOU and EVTOU rate groups. The sample size (i.e., number of unique customer accounts) for each region's rate groups for the study is shown in Table 5.

3. Results

The following sections summarize the results from analyzing the meter-level energy consumption data for the residential customers in the SDGE region. The results are segmented by three main regions, weekday or weekend and the major rate groups – DR, TOU and EVTOU. All load profiles represent the average hourly load for a given rate group.

Table 4

Typical weekend time blocks under TOU plans.

| Rate Class (Year) | Rate | 12 a.m. | 4 a.m. | 8 a.m. | 12 p.m. | 4 p.m. | 8 p.m. |
|-------------------|---------|---------|--------|--------|---------|--------|--------|
| TOU (2016) | DR-TOU | | | | | | |
| | TOU-DR | | | | | | |
| EVTOU (2016) | EV-TOU | | | | | | |
| | EV-TOU2 | | | | | | |
| | DR-E1 | | | | | | |
| | DR-E2 | | | | | | |
| | DR-E3 | | | | | | |
| TOU (2017) | DR-TOU | | | | | | |
| | TOU-DR1 | | | | | | |
| | TOU-DR2 | | | | | | |
| EVTOU (2017) | DR-E1 | | | | | | |
| | DR-E3 | | | | | | |

■ On-Peak
 ■ Semi-Peak
 ■ Off-Peak
 ■ Super Off-Peak
 ■ Other - Single Rate

Table 5

Sample size for each rate group by region.

| Region | Rate Group | Sample Size |
|------------------------------------|------------|-------------|
| San Diego | DR | 634,539 |
| | TOU | 11,305 |
| | EVTOU | 6,109 |
| Coastal Zone (excluding San Diego) | DR | 422,521 |
| | TOU | 7,134 |
| | EVTOU | 7,331 |
| Inland Zone (excluding San Diego) | DR | 427,369 |
| | TOU | 10,466 |
| | EVTOU | 3,487 |
| Total: | | 1,530,261 |

3.1. DR load profiles

The DR rate group represent the most common customer energy profile for any given region. The results closely follow SDGE's overall residential energy load profiles (see Fig. 3). The results for the DR group in San Diego is shown in Fig. 6. The results indicate a peak energy demand in the evening hours similar to the region's overall energy load profile (see Fig. 3). The energy load on weekends tend to be higher throughout the day regardless of time of year.

The results for the DR group in the Coastal and Inland Zones is shown in Fig. 7. The two regions on average have higher loads than the same group in San Diego throughout the year. The Inland Zone has higher loads relative to the Coastal Zone especially during the summer months (Q3). This result is expected because the Inland Zone has higher summer temperatures leading to greater cooling needs. The overall shape of the loads for all regions seem consistent for any given time of

year. There is a single main peak demand occurrence in the evening between 5 and 8 p.m.

3.2. TOU load profiles

The average energy load for customers in the TOU rate group is shown in Figs. 8 and 9 for San Diego and the two climate zones, respectively. Similar to the DR group, the results for the TOU group indicate a peak energy demand in the evening hours. Some key differences between the two groups are the overall higher energy load levels for the TOU group and significantly higher energy loads for the regions outside of San Diego. Compared to the DR group, each region's TOU rate customers consume significantly more energy throughout the day regardless of time of the year. Despite the higher electric rates during peak evening hours, customers under the TOU plans still consume more electricity during the peak hours versus non-TOU plan customers. TOU rate customers in both the Coastal and Inland climate zones consume significantly more energy relative to the comparable group in San Diego. Some factors that may explain this result may be differences in the square footage of homes, income and climate.

3.3. EVTOU load profiles

The average energy load for customers in the EVTOU rate group is shown in Figs. 10 and 11 for San Diego and the two climate zones, respectively. Customers in this group on average have the highest energy load most likely attributable to the EV charging load requirements. Similar to the results in other rate groups, customers outside of San Diego (i.e., Coastal and Inland Zones) have significantly higher energy loads. More importantly, however, all three regions exhibit energy load

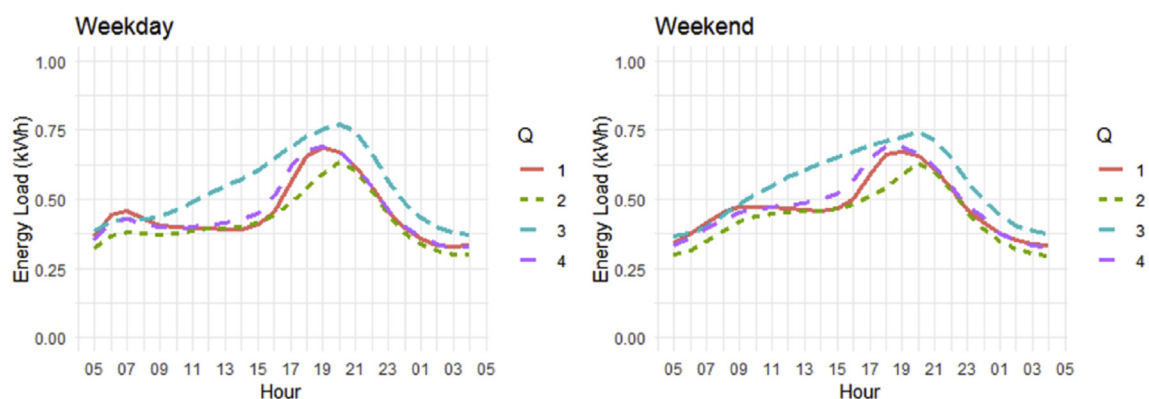


Fig. 6. City of San Diego average hourly load for the DR/DRLI residential rate group (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

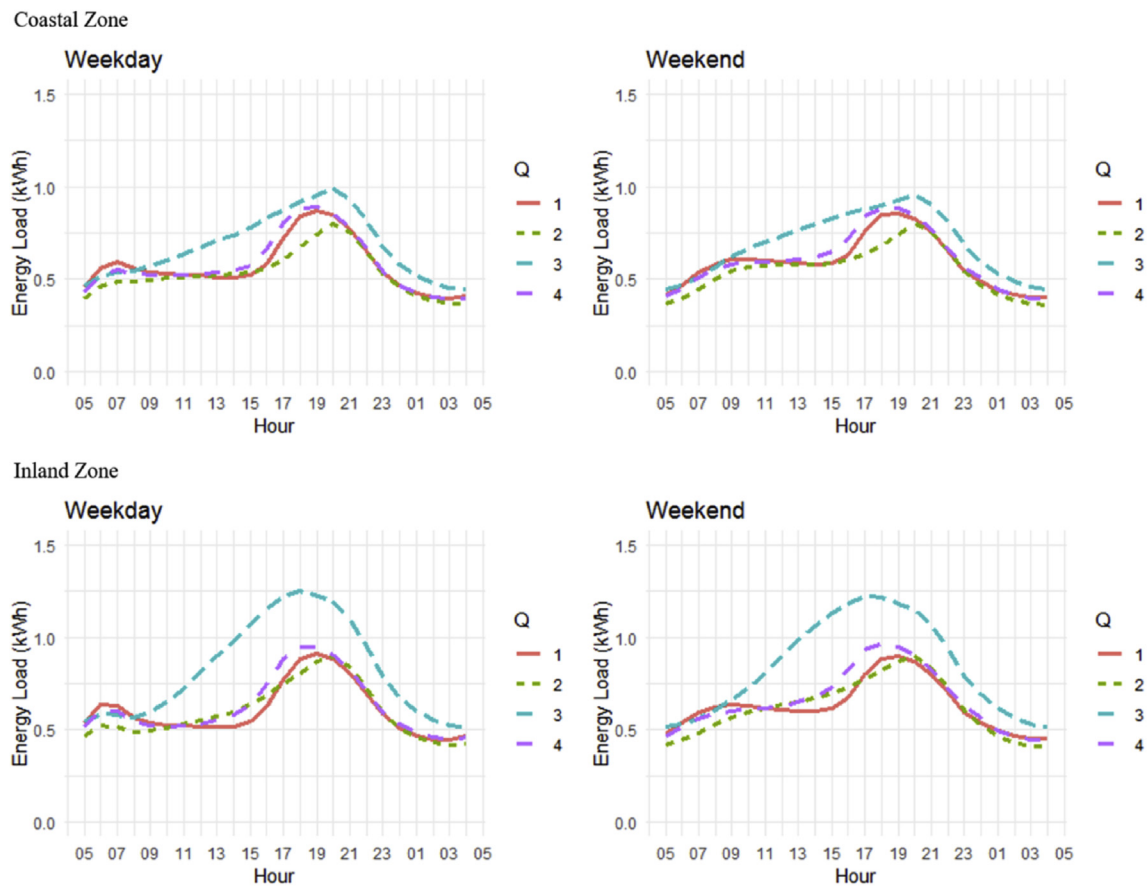


Fig. 7. Average hourly load for Coastal and Inland Zone DR/DRLI residential rate group (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

profiles that have “twin peaks” where two energy peaks arise. The first peak energy demand occurs as expected during evening hours (between 5 and 8 p.m.). A second peak energy demand occurs at midnight regardless of region. This second peak at midnight can be directly attributed to the rate structure. Under the EVTOU plans, there is a super off-peak period that begins at midnight. Since the electric rates are lowest during the super off-peak period, there is a rapid ramping of energy demand at midnight across all regions for this rate group.

4. Conclusion and policy implications

Results from this study have major implications in energy policy and grid operations. Using actual energy meter data, this study captured and analyzed the real-world EV charging behavior in the SDGE service territory. The analysis reveals three main factors:

4.1. EV owners respond to rate plan structure

There was consistent pattern in the energy profiles of customers under EVTOU plans – EV owners begin charging their vehicles at midnight. In all three major regions – City of San Diego, Coastal Climate Zone and Inland Climate Zone – there was major ramp in energy load at midnight regardless of the time of year and day of the week. The main reason for this consistent behavior can be attributed to the incentives set by the TOU rate structure. The most economical electric rate during the “super off-peak” period starts at midnight in all of the EVTOU plans. There is a rapid ramping to a peak load at midnight that decreases quickly in subsequent hours. This finding suggests contradictory evidence to the CEC’s forecasted residential EV charging loads (see Fig. 1). One of the key factors that may be attributed to the finding is the fact that most EV owners can use smartphone applications (“apps”) to easily

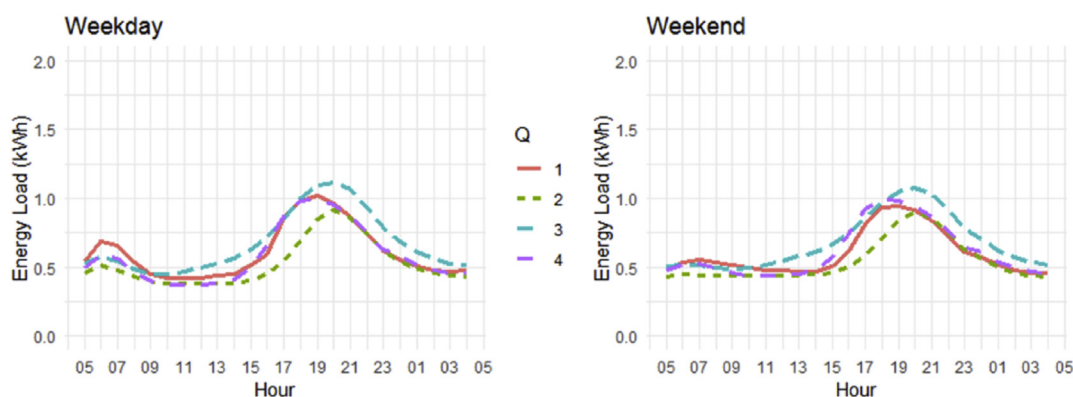


Fig. 8. City of San Diego average hourly load for the TOU residential rate group. (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

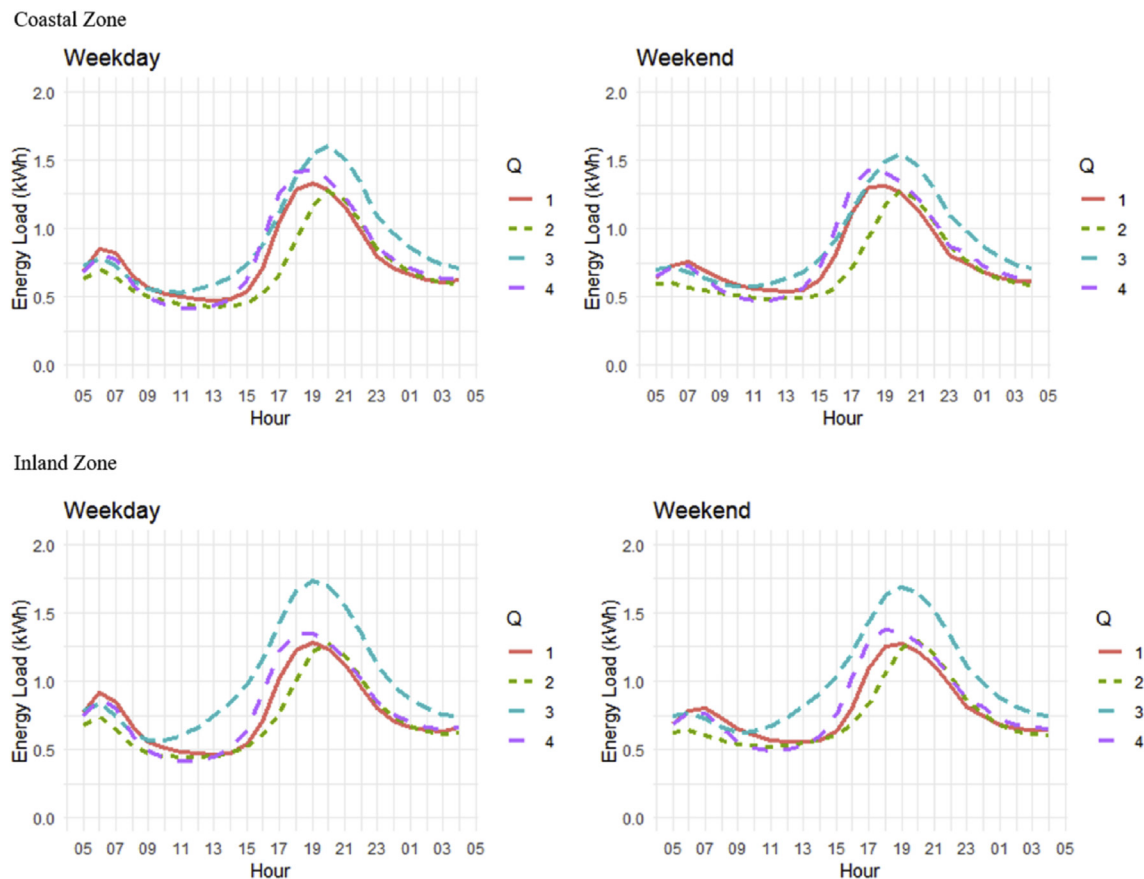


Fig. 9. Average hourly load for Coastal and Inland Zone TOU residential rate group (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

control when the charging to commence. Therefore, EV owners are simply taking advantage of the super off-peak rates by setting the charging time using smartphone apps.

4.2. EV charging creates new peaks

The load profile of the EVTOU groups provides a good proxy measure of the potential EV charging loads because it represents the actual energy usage of residences with EV charging loads. Survey results of EV owners between years 2013 and 2015 showed that roughly 73% of EV owners were under some type special EV electric rate plan (CSE, 2018). It is highly likely that this percentage is even higher in future years due to greater awareness and availability of EVTOU plans. In all regions, EV charging loads creates “twin peak loads” in the load profile. The first peak coincides with the DR/DRLI rate group’s peak load, which is

approximately between 6 and 8 p.m. This peak demand is also consistent with the region’s overall load profile (see Fig. 3). The second peak demand occurs at midnight when the super off-peak period begins for the EVTOU group. Therefore, the second peak demand is directly attributed to EV charging and the structure of the TOU rate plan. The results suggest that residential EV charging loads will create new peak demand rather than simply exacerbate the existing peak demand during evening hours (approximately 6–8 p.m.).

4.3. Rate structure has major impacts

Results reveal the importance of TOU rate structure design. In the standard TOU load profiles, there is a single peak load during evening hours across all regions similar to the region’s non-TOU load profile (e.g., DR/DRLI). In the EVTOU load profiles, however, there are twin

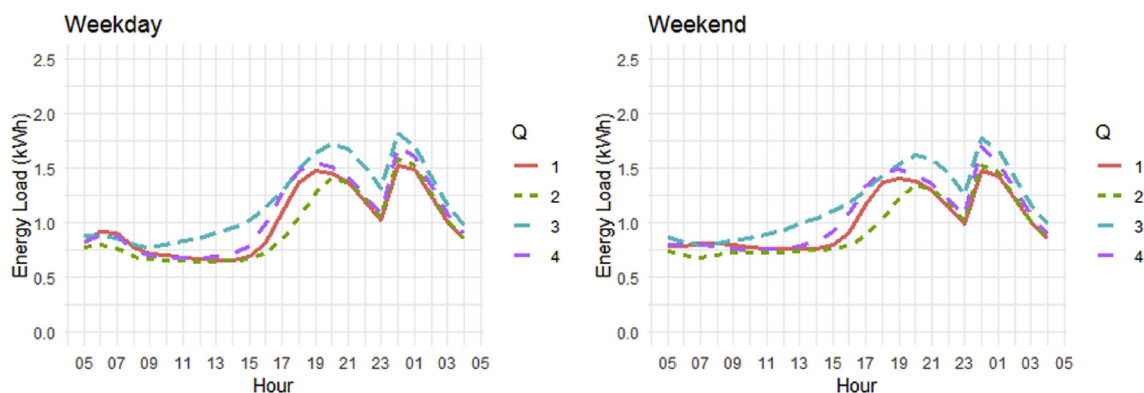


Fig. 10. City of San Diego average hourly load for the EVTOU residential rate group (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

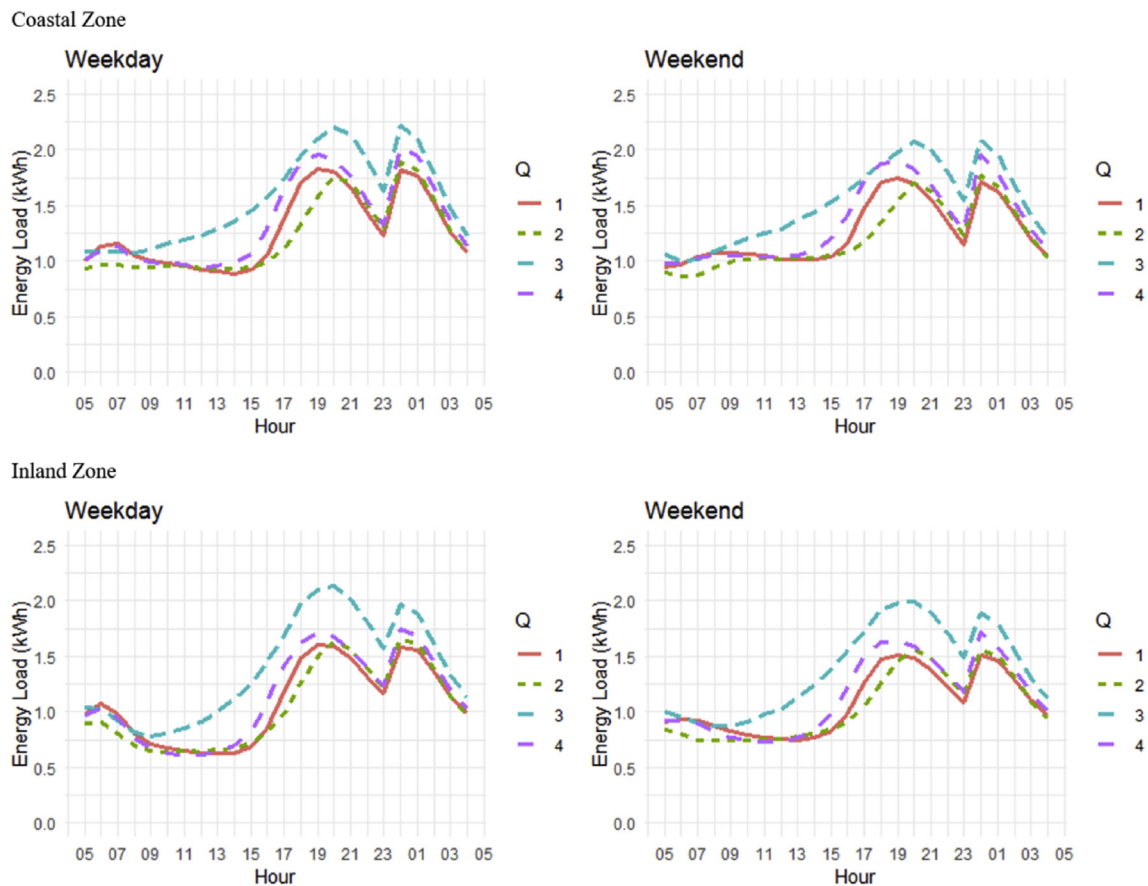


Fig. 11. Average hourly load for Coastal and Inland Zone EVTOU residential rate group (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec).

peak loads with one of the peaks occurring at midnight when the super off-peak period begins. The load also decreases rapidly from midnight to a leveled minimum load within a couple of hours. The explicit choice of midnight as the time when the super off-peak period begins has a direct impact on the occurrence of the second peak demand. Since most EV chargers are controlled easily using a smartphone app, it is highly plausible that EV owners would simply shift the charging activity to the changes in the TOU rate structure. For example, if SDGE were to change its super off-peak period start time from midnight to 2 a.m., then the demand peak would simply shift as well to 2 a.m. Therefore, careful consideration of the TOU rate design is critical to shaping the load profile as more EVs are adopted and charged at homes. Poor TOU rate structure design would lead to unintended consequences such as new peak demand and rapid ramping requirements.

4.3.1. Limitations

This study's scope is limited to residential EV charging in a particular region (i.e., SDGE service territory) so the results may not necessarily be applicable to all other geographical regions. The EV technology also is still in its early adoption stages so the behavior captured in the analysis may be only reflective of early adopters and not necessarily represent the majority/late-adopters of the technology. The current EV population may be prone to self-selection bias in the TOU plans chosen so there is uncertainty in the generalization of the results to a future, larger EV driver population. Furthermore, the charging loads are strongly correlated to driving intensity and patterns so the results may not be applicable to a region with significantly different driving patterns.

4.3.2. Future research work

Results from this study clearly show the importance of TOU rate

structure design with respect to EV charging loads. Poor design of the rate structure can lead to the rise of new energy peaks and other unintended consequences. The necessary next research step is the modeling and simulation of the EV charging loads as a function of different TOU rate structure design and technology adoption rate. For example, the SDGE service territory is expected to experience a significant growth of EVs over the next decade. As more EV drivers are on the road, there will be greater energy demand at the residential sector. An analysis on the potential energy load profiles based on different TOU rate structures across regions and EV charging load requirements would give insights on how to best design the rate structure to induce the best charging behavior for better grid operations.

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